

Absolute detector quantum-efficiency measurements using correlated photons

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Abstract. An experimental system using correlated photons for radiometric purposes has been set up at the National Institute of Standards and Technology (NIST). We use pairs of correlated photons to produce spatial maps of the absolute efficiency of a photomultiplier photocathode at four wavelengths. We also compare this technique with measurements carried out by conventional means tied to existing radiometric standards. These initial comparisons show an average agreement within $\sim 0,6\%$ between the two methods. The results show that correlated photons can be a useful tool in radiometry and that the method holds enough promise to warrant further studies.

1. Introduction

Correlated photons have been shown to hold promise in several areas of radiometric measurements [1, 2]. While several groups have demonstrated that correlated pairs of photons can be used to determine the absolute quantum efficiency of photon-counting detectors without reference to any externally calibrated detector standard [3-8], no high-accuracy independent verification of the method has yet been published. In this work, we compare measurements of detector efficiency carried out by the correlated-photon technique with those carried out by conventional means tied to existing radiometric standards.

The correlated-photon method is based on the process of parametric down-conversion, which produces optical photons in pairs within a nonlinear crystal. Within the crystal, photons from a pump laser beam, in effect “decay” into pairs of photons under the restrictions of energy and momentum conservation. Since the photons are created in pairs, the detection of one photon indicates the existence of the other. Because of the energy and momentum conservation requirements, the direction and energy of the detected photon can be used to predict not only the existence, but also the direction and energy of the other photon of the pair. The fact that one photon indicates the existence of a second photon allows absolute detector efficiencies to be determined.

To test the method, we have set up a system using correlated photons to map the spatial variations of the absolute quantum efficiency of a photomultiplier (PMT) photocathode at four wavelengths. To our knowledge, this is the first time that this method has been used to provide detailed spatial-response maps consisting of direct absolute measurements at each spatial position, rather than a relative-response map which is tied to an absolute scale at only one or a few points. To independently verify the measurement results, a simultaneous measurement of efficiency was made that was tied to an absolute radiometric scale [9]. These initial comparisons are useful to reveal any previously unconsidered systematic effects.

2. Experiment

2.1 Spatial measurement of absolute PMT efficiency

To produce correlated pairs of photons, a linearly polarized Ar⁺ laser, power-stabilized with 30 mW of output at 351,1 nm, was used to pump a KDP crystal (see Figure 1). The input and output ends of the crystal were antireflection-coated for 351 nm and 702 nm, respectively. The crystal was cut so that its optic axis was inclined at 52° to the pump beam direction. The output angles of the correlated photons can be determined from the energy and momentum constraints, the index of refraction data for the crystal and the orientation of the pump beam with respect to the crystal optic axis [1]. This particular configuration yields correlated pairs of photons covering the visible region of the spectrum emitted within a fairly narrow range of angles centred $\sim 4^\circ$ from the pump beam direction. For our four efficiency measurements, we selected pairs of photons at four different pairs of

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wavelengths, shown in Table 1. In addition to the energy and momentum requirements described, the polarization of the pump beam must be oriented parallel to the plane defined by the optic axis and the laser direction. This polarization orientation is required by the parametric down-conversion process defined as Type I, which uses pump radiation polarized along the fast axis of the crystal to produce down-converted light polarized along the slow axis [10]. A half-wave plate was used to rotate the pump beam by 90° , turning off the production of down-converted light to allow for background subtraction.

Table 1. The photons incident on the Si avalanche photodiode (APD) have passed through one of four interference filters with passbands centred on the wavelengths shown. These wavelengths, together with the 351,1 nm pump wavelength, determine the four corresponding wavelengths of the correlated photons incident on the photocathode of the photomultiplier (PMT) being measured.

| | Wavelength/nm of correlated pairs of photons | | | |
|-----------------------------|--|-----|-----|-------|
| Photons incident on the APD | 702 | 608 | 633 | 788,6 |
| Photons incident on the PMT | 702 | 831 | 789 | 633,2 |

A dry-ice-cooled Si avalanche photodiode (APD) was used to detect the presence of the down-converted light. To detect individual photons, the APD was operated in the geiger mode [11] with a bias voltage of 221,9 V (this is ~ 40 V above breakdown). The output pulses, without any electronic amplification, were very smooth pulses about 1,5 V in amplitude and less than 3 ns in width. These pulses were sent directly to the start input of a time-to-amplitude converter (TAC). The TAC “valid starts” output was sent to a counter to record the APD counts. No lens was used in front of the APD, so the detector diameter of 0,5 mm and the 81 cm distance from the crystal defined the 0,62 mrad collection angle. Four different interference filters with 2 nm to 3 nm passbands were used individually to limit the light on the APD; these passbands also fixed the wavelengths of the PMT calibration, see Table 1. The APD was mounted on a manually operated $x - y$ stage to allow the APD position to be centred on the peak of the down-converted light within the filter passband.

The PMT (Burle [12] model C31034A), whose spatial response was to be measured, was placed to intercept the portion of the down-converted light correlated with the light detected by the APD. A lens positioned in front of the PMT was used to focus all of the light correlated with the APD onto the PMT photocathode producing a small spot $\sim 0,25$ mm in diameter. Four different interference filters with 10 nm to 20 nm passbands, encompassing the calibration wavelengths shown in the lower line of Table 1, were used to limit the light incident on the PMT. (It is important that the bandpass of the PMT filter be wider than the APD filter bandpass, so that all of the photons

correlated to the APD light pass through the PMT filter. This configuration reduces the sensitivity of the quantum-efficiency measurement to slight shifts of the centre wavelength of the PMT filter.) The PMT was cooled thermoelectrically to $\sim -30^\circ\text{C}$ and mounted on a computer-controlled $x - y$ positioning stage. The PMT socket was built following recommendations for producing fast pulses with minimal ringing [13]. The pulses were amplified using two $5x$ fast-pulse amplifier stages. The signal was then sent to an amplifier/discriminator with a manually set threshold level. The amplifier/discriminator provided about 40 ns of delay between the input and output pulses. The discriminator output was then sent to the TAC stop input and to a counter to record the PMT counts.

The TAC output was sent to a multichannel analyzer (MCA) producing a histogram of delays between start and stop events. Correlated photons were seen as a coincidence peak in this histogram at a delay time corresponding to the total time difference between the two channels due to optical and electronic path differences. The counts in a region containing the coincidence peak and the counts in a background region away from the peak were recorded by computer. The background level was subtracted from the coincidence peak to determine the true number of coincidence events. Both the MCA and the counters recording the individual APD and PMT counts were gated simultaneously under computer control so that all gate times were identical.

The APD and PMT counts not due to down-converted light were determined by rotating the pump polarization 90° with a half-wave plate, effectively turning off the down-converted light. These counts ($\sim 5\%$ of the total signal) were subtracted from the individual counts of the detectors with the proper pump polarization. The ratio of the coincidence counts to the APD counts after zero subtraction is the absolute quantum efficiency of the entire PMT optical system including all optics such as windows, the lens and the filter. The absolute quantum efficiency of the PMT was spatially determined as its position was scanned in x and y in 0,25 mm steps (see Figure 1) with 10 s gate times.

2.2 Comparison between correlated and conventional efficiency measurements

To independently verify the efficiency of the PMT, we measured the total power of the down-converted light incident on the PMT using a Si photodiode detector/amplifier package capable of gains up to 10^{11} V/A and tied with a 1σ uncertainty of 0,37% to an absolute scale using the Visible/Near Infrared Spectral Comparator Facility [14] at the NIST. The comparison was done by substituting the Si diode for the PMT without changing any other component of the optical path. Using the light power determined by the Si diode and the individual count rate of the

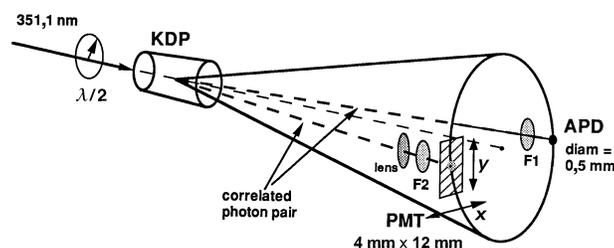


Figure 1. Scheme for x - y mapping of detector efficiency and comparing with conventional measurements. The grey spot on the PMT photocathode indicates the region containing photons correlated to those detected by the APD. The two interference filters are designated F1 and F2. The half-wave plate is designated $\lambda/2$. The conventional measurement is made by substituting the Si detector for the PMT.

PMT, the PMT efficiency can be calculated. These measurements were made both before and after the correlated measurements. The stability of the down-converted light during the interim depended on the stability of the pump laser light stabilization mode. The wavelength chosen for this comparison was 633,2 nm.

Since the correlated technique measures the efficiency of the entire optical path, in addition to the PMT itself, it is necessary to separately determine the transmittance of that path. The transmittance of the KDP crystal and the lens were measured using a laser at 632,8 nm. The transmittance of the filter was measured with the same facility used to calibrate the detector/amplifier. The transmittance from the centre of the KDP crystal to the entrance of the PMT housing was measured to be 0,565 with a 1σ uncertainty of 0,94%. The three largest contributions to this uncertainty were from the interference filter whose transmittance varied by an estimated 0,5% over the range of incident angles of the down-converted light, varied by 3,2%/nm across the central 4 nm of its passband and varied by $\pm 0,4\%$ spatially across its surface. These variations along with an uncertainty in the position of the APD passband and corresponding uncertainty in the PMT calibration wavelength resulted in a 1σ uncertainty in the effective filter transmittance of 0,78%.

To properly make this comparison, effects of the dead times of all parts of the system need to be considered. The dead time of the PMT along with its amplifiers and discriminators was independently measured to be 42,5 ns. The largest contribution to this dead time was the output pulse width of the amplifier/discriminator. At the count rates used for this test, the dead-time correction to the PMT individual count rate was an average of 1,25%. We expect that dead time in the PMT channel, which is used to stop the TAC, should not affect the rate of correlated counts. This is because one PMT count will stop the TAC and any subsequent dead time is irrelevant. This expectation has not been tested experimentally and should be verified in the future. The dead time of the APD should not affect the correlated result, which

is the ratio of correlated counts to APD counts, because both the components are reduced by the same fraction. The APD background level does, however, need to be corrected for dead time since the dead time loss for the signal on and signal off measurements is different. The apparent APD dead time was found to be 46,5 μ s. This long dead time was due mainly to the fact that the APD pulses decrease in amplitude as the count rate increases, causing the counts to slip under the detection threshold of the TAC. Correction of the correlated measurement of PMT efficiency amounted to $\sim 3,5\%$ at the APD count rates used in these measurements. The uncertainty of this correction contributed a 1σ uncertainty of 0,1% in the correlated efficiency.

3. Results

The spatial maps of the absolute efficiencies of the PMT (and optics system) at the four calibration wavelengths are shown in Figure 2. The observed rectangular shape and size of the responsive region are as expected for this particular photocathode. The sharpness of the edges in both the horizontal and vertical directions indicates that the spot size at the photocathode, which determines the spatial resolution of the measurements, is less than the scan step size of 0,25 mm. The PMT to lens distance was adjusted to produce the sharpest edges. The overall efficiency of the PMT/optical system at 702 nm, of about 5,4% with a 1σ spread of 0,5%, is consistent with the estimated value of 6,6% based on the manufacturer's data sheet (13%) and the measured transmittance of the optical path (51%). Since the uncertainty of the data from the manufacturer is unknown, an independent measurement of the PMT/optical system response was required.

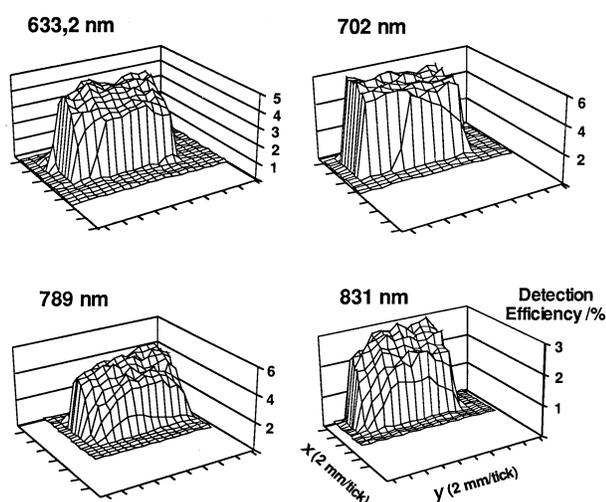


Figure 2. Absolute responsivity maps of the PMT/optical system at four wavelengths. The x and y scales of 2 mm/tick apply to all four maps.

The independent measurement of PMT response was performed at four points on the photocathode surface at a single wavelength of 633,2 nm. When this comparison was made, several months after the spatial maps, we found that the PMT response had severely degraded and was continuing to decline rapidly. Decreases of 10% in response over 15 hours of observation were clearly visible. As no suitable replacement was available and as the individual counts used for the conventional measurement and the coincidence counts used for the correlated measurement were recorded simultaneously, we felt that a useful comparison could still be made, in spite of this problem.

The correlated-efficiency measurements of the four points are shown in Table 2. The comparison of the conventional with the correlated measurements of efficiency is shown in Figure 3. The differences and uncertainties are relative to the correlated result. The average relative difference was 0,63 %, well within the estimated 1σ error bars (which averaged 1,7 %).

Table 2. Comparison of conventional and correlated-photon measurements of efficiency at four points on the photocathode of a photomultiplier. The numbers for values of efficiency have been rounded.

| Sample point | Conventional efficiency meas./% | Correlated efficiency meas./% | Relative diff.% | Relative 1σ uncert./% |
|--------------|---------------------------------|-------------------------------|-----------------|------------------------------|
| 1 | 0,260 | 0,259 | -0,55 | 1,6 |
| 2 | 0,313 | 0,316 | 0,76 | 1,5 |
| 3 | 0,372 | 0,384 | 3,13 | 1,6 |
| 4 | 0,288 | 0,286 | -0,83 | 2,2 |
| Average | | | | |
| 0,63 | | | | |

(CORRELATED EFFICIENCY - CONVENTIONAL EFFICIENCY) X 100 / CORRELATED EFFICIENCY

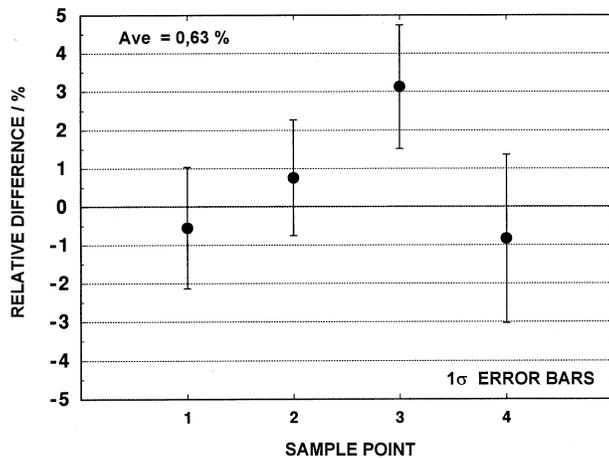


Figure 3. Comparison between conventional and correlated measurements of efficiency. The difference relative to the efficiency measured by the correlated method is shown for four different points on the PMT.

4. Conclusions

The results presented here demonstrate that the spatial variation of the absolute response of a photon counting system can be measured at a range of wavelengths using correlated light. The accuracy of the method has been initially verified with an average agreement between the correlated and conventional measurements of 0,63 % which is well within the average estimated 1σ uncertainty of 1,7 %. The observed level of agreement indicates the robustness of the method, even when faced with a PMT suffering from rapid degradation of response and an APD measurement channel with 40% dead time. It is expected that modifications such as replacement of the APD with an actively quenched version, replacement of the PMT with a healthier detector, and continuous monitoring of the down-converted light power should provide even higher accuracy verifications of the correlated photon method. This work is relevant not only to absolute detector-efficiency measurements, but also to other interesting applications such as measurements of infrared radiation using visible detectors and absolute measurements of absolute sources. These results show that correlated photons can indeed be a useful tool in radiometry and that the method holds enough promise to warrant further studies.

Note. Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

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